THE USE OF BUILDING INTEGRATED PHOTOVOLTAICS (BIPV) TOWARDS ULTRA ENERGY EFFICIENT BUILDINGS

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THE USE OF BUILDING INTEGRATED PHOTOVOLTAICS (BIPV) TOWARDS ULTRA ENERGY EFFICIENT BUILDINGS

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To my Family and Friends

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TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

LIST OF EQUATIONS

LIST OF CHARTS

SUMMARY

The study covered in this thesis basically covers Building Integrated Photovoltaic (BIPV) as a fenestration component and its application across different commercial buildings across United States of America.

It first covers the material identification for the BIPV, which ends up with Dye-Sensitized Solar Cell as the material used in the BIPV. Then two different BIPV models were computationally designed using the Lawrence Berkeley National Laboratory's Tool – WINDOW, where first model was basically a double pane window with DSSC filled between the two panes of window while the second model was a three pane window with DSSC and Inert gas filled between 1st & 2nd pane, 2nd & 3rd pane respectively.

Then three different commercial building were considered for study, which came from the reference buildings of Department of Energy, namely –

1. Small Scale Commercial Building (Post 1980 construction)
2. Medium Scale Commercial Building (Post 1980 construction)
3. Large Scale Commercial Building (Post 1980 construction)

Then another parameter of variability was introduced for having the wider coverage of the cases, as Window to Wall Ratio (WWR). Most commonly used WWR such as 40%, 60% and 80% were considered for each of the East, West and South facades of the building, making 27 unique combinations of WWR. It was assumed that North façade would not have BIPV because of the lower solar radiation on the north façade.

Then five different climatic zones were considered to understand the relevance of BIPV across United States, namely –

1. Atlanta,
2. Chicago,
3. Los Angeles,
4. Miami,
5. Phoenix

Then each of these combinations of BIPV windows, WWR, Building type and Climate/cities was evaluated and analyzed for the energy savings. Later on these energy savings value was subjected to hypothetically designed Peak Demand Electricity Pricing model, which ended up identifying the most relevant combinations in favor of BIPV.

CHAPTER 1. INTRODUCTION

As we know that world is gradually approaching towards the energy crisis, there exist an acute requirement of energy efficiency. In this situation, it becomes important that not only the dependence on renewable energy sources should be increased, but it also requires going for more energy efficiency. Actually depending on the renewable energy sources solves the supply side of this crisis while going energy efficient solves the demand side of the problem. This study is basically an approach, which takes care of both of these aspects i.e., supply side of the problem as well as demand side of the problem.

Building Integrated Photovoltaic is basically a kind of photovoltaic system itself, but apart from being a regular photovoltaic panel, it is integrated to the building and serves for some of the functional aspects of the building. Therefore, it makes more sense to consider the feasibility of BIPV as a solution for the ultra energy efficient buildings because in terms of on-site energy production or generation, currently most common option exists in the form of photovoltaic panels which has a significant limitation in terms of the area allocation for its installation. On the other hand BIPV exists as one of those options which is not just limited by the roof area of the buildings, rather it can be installed as the façade of the buildings and this feature opens the whole new scope of extra on-site electricity generation to avoid the Peak Demand Charges and deal with the Time-of-Use electricity pricing mechanisms. It can also serve as a good solution particularly in the case of stand-alone buildings, which are especially off the electric grid.

This study has also been undertaken with the purpose of showing the possibilities of reaching the ultra energy efficiency levels in the buildings, especially commercial buildings. In order to achieve this objective, this study has been diversified at different levels to see the suitability of this BIPV technology under different conditions, such as types of BIPV models used, Scale of Buildings used, Climatic conditions for the building locations, Commonly used combinations of Window to Wall Ratio, Different electricity Pricing models, etc. Considering these many variables will help the market and industry for making a brief idea about their project or buildings, without getting much into the dynamic simulation modeling. Rather, this study can also be seen as a parametric tool for the decision making of whether to get into a dynamic simulation for the installation feasibility of BIPV's.

CHAPTER 2. LITERATURE REVIEW

2.1 Necessity of Solar Development

Consumers have used fossil fuels as the main energy source because it is inexpensive and conveniently used. Although this energy source accelerated the advance of human civilization, the development of alternative renewable energy sources is imperative to avoid undesirable environmental consequences. Buildings are main consumers of energy and it is not surprising that increasingly technologies are introduced to improve their energy efficiency, and add on site electricity generation technologies. The most popular in the latter category is PV, but usable surfaces (typically the roof) are limited. Other building integrated electricity generation technologies are therefore considered and one of them is the subject of this study, i.e., window integrated generation through DSSC technologies (dye-sensitized solar cells). DSSC and organic photovoltaic (OPV) are emerging photovoltaic technologies that have exhibited enormous improvements in recent years and have further developed as a potential for future commercialization [1]. Incidentally, DSSCs are currently the most efficient third-generation solar technology available [2]. Recently, observed energy efficiency reached up to 13 to 15% [3, 4]. This product has low production costs and interesting technical features, including transparency, ease of processing and stability. Enhancing the three main components of the cell—organic dye, nano-crystalline semiconductor and redox couple in the electrolyte—is of paramount importance for optimizing the performance of the devices. [5]

2.2 Principle of Dye-sensitized Solar Cell (DSSC)

In 1991, the Grätzel group of Swiss EPFL reported a DSSC that exhibited high energy conversion efficiencies and showed low-priced production costs similar to amorphous silicon solar cells [6].

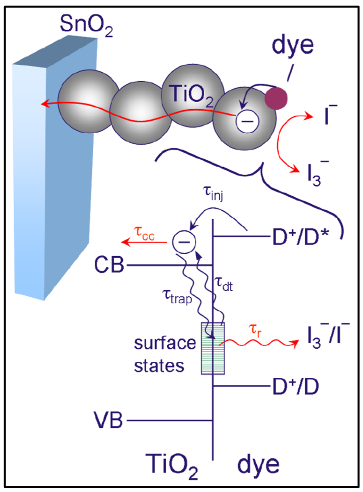


Figure 1: Photoelectric transmission of DSSC and energy level between the elements

Figure 1 shows the principle mechanism of DSSC operation [7]. When the sunlight (visible rays) is absorbed into the surface of an n-type semiconductor oxide electrode, the dye molecule makes electron-hole pairs, and the electrons are injected into the conduction band of the semiconductor oxide. These electrons produce a current by being transmitted to the transparent conduction membrane through the nano-particle interface. Hole production within the dyes receives the electrons from the oxidation-reduction electrolyte again and completes the mechanism of action [8].

To put it simply, the general chemical reaction formula can be understood below.

Dye + Sunlight → Dye*(excited state)

$Dye^* + TiO_2 \rightarrow e^-(TiO_2) + Dye^+$

$Dye^+ + \frac{3}{2}I^- \rightarrow Dye + \frac{1}{2}I_3^-$

$\frac{1}{2}I_3^- + e^-(\text{counter electrode}) \rightarrow \frac{3}{2}I^-$

Total chemical reaction: $\frac{1}{2}I_3^- + e^-(TiO_2) \rightarrow \frac{3}{2}I^-$

The first three processes occur at the TiO_2 electrode where the dyes are absorbed; the fourth process occurs at the counter electrode. A Ruthenium dye absorbs the light energy transmitted to the excited state from the ground state. Two processes proliferate the electrons: (1) electron injection into the semiconductor conduction band from non-thermalized singlet excited state and (2) the injection of thermalized electrons which move to triplet excited state through the internal vibration-relaxation process [9, 10]. Note that the electrons are injected in only femto seconds, and the oxidized dye is reproduced in only nanoseconds [11]. Since the recombination speed is slow (micro-milliseconds), most photoelectrons are injected into the semiconductor conduction band. Since these photoelectrons are involved in the electron delivery, high photoelectric energy conversion efficiency and long-term safety are proved experimentally [12].

2.3 Materialization of DSSC

2.3.1 Nano-particle Semiconductor Oxide Materials

Since the high specific surface area of nano-sized materials allow absorption of many dye molecules, nano-crystalline materials (diameter ~ 20nm) are being used as the electrode material for absorbing dyes. However, this also creates a disadvantage; the increased number of surface states provides recombination sites. Therefore, the technology that can control the size, morphology, crystallinity, and surface state becomes one of the important research subjects in DSSC. When selecting the nano-semiconductor oxide for DSSC, the first thing that should be considered is the energy value of the conduction band. The conduction band energy of a semiconductor should be lower than lowest unoccupied molecular orbital (LUMO) of the dye. Currently, the most frequently being used oxide is TiO_2 because its conduction band energy is 0.2eV lower than LUMO of the ruthenium dye (ex: N3, N719).

Until now, TiO_2, SnO_2, ZnO and Nb_2O_5 etc. have been researched, and the best efficiency was shown from TiO_2. Three phases of TiO_2 are known: anatase, rutile, and brookite. The anatase phase is stable at low temperatures while the rutile phase is stable at high temperatures. The anatase TiO_2, which has dozens of small circular particles, is available to be made by hydrothermal synthesis; the rutile TiO_2 can be made by hydrolysis synthesis at room temperature.

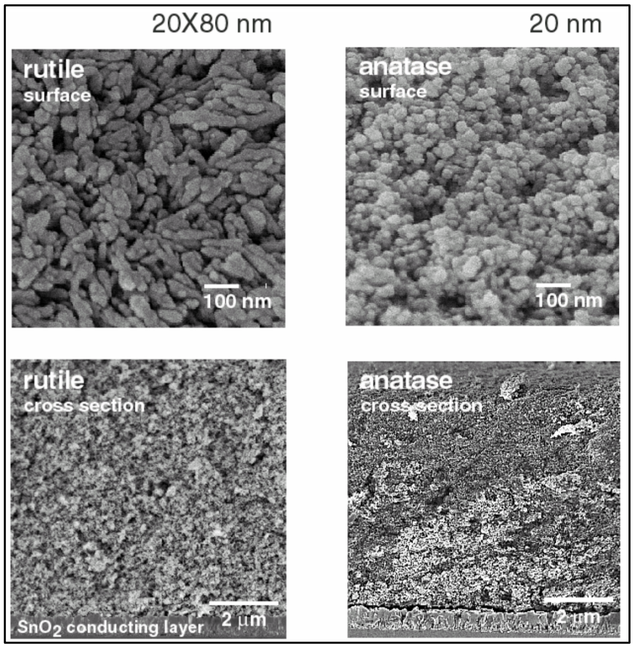


Figure 2: SEM images of anatase and rutile TiO2 surface

Figure 2 shows SEM images of the typical nano-crystalline structure of anatase and rutile TiO_2 films [13]. The anatase TiO_2 film shows densely packed 20nm diameter circular particles, but the rutile TiO_2 film shows loosely packed 80nm diameter nano-stick particles. So the anatase TiO_2 film, which has high specific surface area, produces more photoelectric current than the rutile TiO_2 film. The particle size and the morphology effect on the diffusion rate of electrons has been experimentally proven, showing that a lower porosity increases the rate of electron diffusion as follows [14].

$D \propto |P - 0.76|^{0.82}$ (D: Diffusion rate, P: Porosity)

2.3.2 Photosensitive dye materials

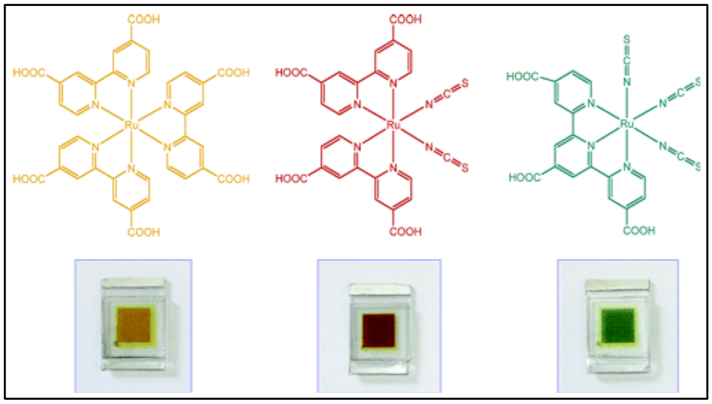


Figure 3: Color change of dyes depending on its ligand structure [15]

Well known that DSSC dyes are ruthenium organic-metallic compound as well as organic compounds and quantum dot inorganic compounds like InP, CdSe. The first condition that the dye for DSSC needs to satisfy is that it should be able to adsorb the full spectrum of visible rays. Moreover, it should have solid chemical combination with the nano-oxide surface and should be thermally and optically stable. Until now, the ruthenium organic-metallic compound is known as the best choice. The ruthenium dye has the ruthenium at the center, and pyridine ligand and SCN ligand are coordinated around it. When the number of pyridine rings increases from 2 to 3 and 4, peak charge transfer from metal to ligand is determined by a long wavelength and small adsorption coefficient. Figure 3 shows the typical ruthenium dyes: N719, N3 and N749 respectively. Recently researched dyes containing triphenylamine organic material show up to 9% energy conversion efficiency [16]. But in case of the organic material, problem arises from the thermal and optical instability. Therefore, it will be great in the view of cost if the stability can be assured.

2.3.3 Oxidation – Reduction Electrolyte

The electrolyte for DSSC consists of oxidation-reduction reactions such as I^- / I_3^-. The sources for the ion I^- are LiI, NaI, and Alkaline Ammonium Iodine, while I_3^- is created by dissolving I_2 in solvent. Liquid acetonitrile or PVDF (polyvinylidene fluoride-co-hexafluoropropylene) polymers can be used as a medium for the electrolyte. Ion I^- provides the electrons to the dye molecule, and the oxidized I_3^- receives the electron at the electrode and is reduced to I^- again. On one hand, the liquid acetonitrile can yield high-energy conversion efficiencies because of its rapidity in the reproduction of the dye; however, leakage can occur when the electrode junction is not perfect. On the other hand, the PVDF polymer can prevent the leakage problem but will reduce the energy conversion efficiency due to a deceleration of the oxidation-reduction reaction. Therefore, the design for increasing its reaction needs to be developed. PAN (polyacrylonitrile), PVDF, acrylic-ionic liquid compound, pyridine, PEO (polyethylene oxide) and others have been researched as a polymer electrolyte.

CHAPTER 3. METHODOLOGY

3.1 Research Design

3.1.1 BIPV Modelling

This study starts with the sizing of Building Integrated Photovoltaic unit, commonly referred as BIPV. I started with a standard unit of fenestration for the building, which is basically a Double Pane window unit with inert gas filling in between the two panes of the windows. This model will be referred as Standard Unit or Business As Usual (BAU) window. Then I modeled an enhanced version of this fenestration unit by replacing the inert gas filling from DSSC and keeping the remaining setup as it is. This model will be referred as Double Pane Window with DSSC or Model 1. Then I also modeled second upgraded version of this window in the form Three Pane Window with two cavities in between of these three panes of glasses filled with DSSC and inert gas respectively, where DSSC is closer to the outside and inert gas closer to the inside surface of the building. This model will be referred as Triple Pane Window with DSSC and Inert gas or Model 2. Table 1 shows the thermo-physical parametric values for all of these three types of windows that have been considered for this study.

3.1.2 Building Modelling

In order to evaluate the performance and feasibility of the use of this type of BIPV, I started with three different buildings. In order to keep the results general, I decided to go with three of the Department of Energy’s reference buildings, namely Post 1980 Large Scale Office Building, Post 1980 Medium Scale Office Building and Post 1980 Small

Scale Office Building (http://energy.gov/eere/buildings/existing-commercial-reference-buildings-constructed-or-after-1980). The purpose of doing so was to figure out that at what scale it will make sense to go for BIPV.

Then, to add some level of variability to these buildings, it was decided to go with different commonly used Window to Wall Ratio i.e., 40%, 60% and 80% and the purpose of doing so was mainly to consider the most encountered building cases. So basically all of the possible combinations of 40%, 60% and 80% are considered for the East, West and South facades of these buildings. The North facade was not considered for the installation, keeping in mind about the less exposure to the solar radiation.

Table 1, shows the 27 different combinations of Window to Wall Ratio (WWR), considered for this study, along with their ranking for expected energy generation in ascending order.

3.1.3 City/Climate Modelling

Then, I also considered the applicability of this study in most of the possible climatic conditions and based on this thought I considered five different climatic conditions of United States, namely, Atlanta, Chicago, Los Angeles, Miami and Phoenix. Table 2, shows the details of the climates considered for this study.

3.1.4 Energy Performance Standard Calculation Toolkit Case Study

A tool developed by a Georgia Tech student was accessible for our use. The Energy Performance Standard Calculation Toolkit is an excel document that receives weather information, building parameters, and load profiles to estimate the average annual energy demand. The goal of using this program was to incorporate DSSC into the software in order to determine its effects on energy demand. In order to evaluate the potential of DSSC in the context of the real buildings, we decided to evaluate the Clough building. For modeling the building, we had few assumptions, which are as follows:

- Only the glass façade of the existing building will be considered as the potential for the installation of the DSSC based PV.
- Only north, west and south facades will be considered for the installation because the solar exposure on the east façade was negligible.

The decision of the building selection was based on the following assumptions:

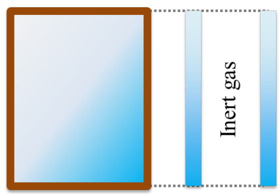
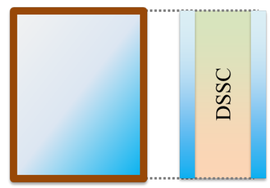
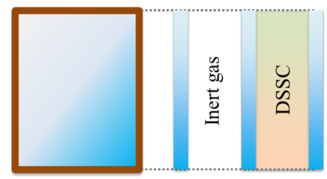
- Building should already be energy efficient
- Have a considerable area for the glazing on exterior facades of the building.
- Have a good exposure to the sun on Non- east facades, especially on south and west

Parameter values can be located in modeling section. The next step in this evaluation was to determine the solar PV and DSSC contributions to our model. This evaluation runs through a sequential process; computations made throughout this discussion refer to direct steps as marked.

3.2 Cases Considered

Types of window or fenestration units considered in this study along with their schematics have been listed in Table 1.

Table 1: Schematics and concepts of three window models considered for this study

S. No.	Standard Model	Model 1	Model 2
Schematics			
Name	Business As Usual Model	Double Pane Window with DSSC	Triple Pane Window with DSSC and Inert gas

In order to understand the effect of change in area allocation for the BIPVs, I ranked the different combinations of Window to Wall Ratio (WWR). Ranking of these combinations are based on the following order –

1. Overall Area allocated for the BIPV in each of the buildings.
2. Once overall area matches, then priority goes to the area allocated on the South façade, followed by West façade and then East façade.

Table 2: WWR combinations and their ranking

Combination code	East	West	South	Ranking for energy generation
1	0.4	0.4	0.4	1
2	0.6	0.6	0.6	14
3	0.8	0.8	0.8	27
4	0.4	0.4	0.6	4
5	0.4	0.6	0.4	3
6	0.6	0.4	0.4	2
7	0.4	0.6	0.6	9
8	0.6	0.4	0.6	7
9	0.6	0.6	0.4	6
10	0.4	0.4	0.8	10
11	0.4	0.8	0.4	8
12	0.8	0.4	0.4	5

Table 2 (continued)				
13	0.4	0.8	0.8	23
14	0.8	0.4	0.8	21
15	0.8	0.8	0.4	18
16	0.6	0.8	0.8	26
17	0.8	0.6	0.8	25
18	0.8	0.8	0.6	24
19	0.6	0.6	0.8	22
20	0.6	0.8	0.6	20
21	0.8	0.6	0.6	19
22	0.8	0.6	0.4	11
23	0.8	0.4	0.6	13
24	0.6	0.8	0.4	12
25	0.6	0.4	0.8	16
26	0.4	0.6	0.8	17
27	0.4	0.8	0.6	15

It is based on the fact that South facade will experience the after noon hours when the intensity of solar radiation is highest, while the rising sun from East in the morning will have the lowest intensity of solar radiation. I assumed that North facade would be symmetric to the South façade and that decides the area allocation for Windows or fenestration on the North façade.

Table 3: Climates Considered and their Classification

Serial No.	City	Climate
1	Atlanta, Georgia	Temperate / Humid Subtropical Climate
2	Chicago, Illinois	Continental Climates
3	Los Angeles, California	Temperate/ Mediterranean Climates
4	Miami, Florida	Tropical Monsoon Climates
5	Phoenix, Arizona	Dry and Arid Climates

CHAPTER 4. MODELING AND EXPERIMENTS

4.1 Window Modeling

4.1.1 Material selection

For applying DSSC to existing buildings, commonly used materials will be initially used. Also, we focus on especially low-priced materials, which is one of the main advantages of DSSC. In the electrode, mesoporous TiO_2 is chosen to be applied, since it is still the most commonly used metal semiconductor. It is low-cost and can be processed into transparent films with large interfacial area; this allows high loads of dye and high electron mobility [17]. Overall, TiO_2 produces the best results compared with other alternative oxides. In the dye, the ruthenium organic-metallic compound can yield high efficiency; however, it is expensive. Therefore, I rather choose commonly used cheap organic dye—anthocyanin—as the dye material. The other versatile dyes will be able to be applied in a future study after this base framework on DSSC application is achieved. For the electrolyte, only the liquid electrolytes were considered due to their applications as opposed to solid/ polymer mediums. While there are unfavorable properties of liquid electrolytes, such as corrosiveness, leakage and volatility, efficiencies of solid mediums have not approached those of liquid electrolytes [18]. Thus, I selected the liquid I^-/I_3^- electrolyte because of its commonality and reliable performance [19]. In the later part, I will discuss energy performance results of the DSSC when applied to a building.

4.1.2 Window simulation

Window simulation variables were divided into three different types of glazing systems as shown in Table 1. As a reference point, a double glazed window filled with inert gas was considered. For the experimental case, a double glazed window filled with DSSC instead of inert gas was considered. For a final solution, a triple glazed window filled with DSSC and inert gas in each gap was considered.

Within the experimental case, two additional models were prepared to determine performance when inserting glasses with different solar transmittance. Experiment 1 is same as the real case to see the result when only the gap material is replaced by DSSC while experiment 2 is same DSSC material with one filled in the gap but with using lower solar transmission glass material. This case will show how the solar transmission affects energy performance.

For the energy performance calculation, key properties needing to be applied are thermal transmittance, emissivity and solar transmittance. The glazing performance calculation was executed using free software provided by Lawrence Berkeley National Lab, the WINDOW LBNL simulation tool [20]. WINDOW LBNL analyzes products from any combination of glazing layers, gas layers in the gap, frames, spacers, and dividers under any environmental conditions and at any tilt.

The process to achieve the above proposed glazing systems are as follows –

a) Choose the glass material of real case in WINDOW LBNL. The glass material should be the one, which the combination with inert gas yields same value with referenced existing value [21].
b) Design the geometry and dimensions of the glazing systems.
c) To run the calculation, insert the values of glass and gap materials to each glazing systems, real case and experiment 1 case. Use the glass material value achieved from a) and DSSC value selected from section 4.1.
d) Repeat c) with using different glass material which has lower solar transmittance. This different glass material value will be put into the experiment 2 case and solution case. Solution case has referenced glass material at the outermost glass of DSSC side while the low solar transmittance glass material is at the other two glasses of inert gas side.

In the case of solution glazing system, we tried to combine both the effects of the inert gas and DSSC. To be specific, we designed the solar radiation as being transmitted into the DSSC sufficiently to generate the electricity. At the same time, we designed the reduced solar transmittance for the glass panes so that buildings can maintain their controlled condition (heating and cooling) inside.

Material and geometrical properties that WINDOW LBNL needs for calculation have been listed in Table 4, while Table 5 shows the thermo-physical characteristics of the modeled window. This information will be clarified in the context of overall building energy consumption.

Table 4: Input values for Window modeling in LBNL's WINDOW tool

Serial No.	Parameters	Values
1	Dimensions	1000 x 1000 x 12.7 mm^3 (glass) / 12mm (gap)
2	Glasses	0.603 (solar transmittance, real case) and 0.200 (solar transmittance, low transmittance)
3	Inert gas	Air 10% / Argon 90% mixed gas
4	DSSC	7.7 W/m·K (conductivity), 0.002 kg/m·s (viscosity) [22, 23]

Table 5: WINDOW LBNL simulation results of real, experiment 1, experiment 2 and solution case

Type	U value [W/m^2·K]	ε [-]	T [-]
Real	2.371	0.248	0.565
Exp. 1.	4.833	0.249	0.564
Exp. 2.	4.856	0.544	0.286
Solution	2.257	0.648	0.225
Final Model	**U- value (w/m2.K)**	**ε [-]**	**T [-]**
Business As Usual Model- Double Glaze with Inert Gas	2.33	0.6	0.6
Double Glazing Model with DSSC	5.58	0.08	0.83
Triple Glazing Model with DSSC and Inert Gas	2.35	0.63	0.23

4.2 Building Modeling

As mentioned here, building modeling is mostly guided by the details of the Post 1980 Commercial building from Department of Energy website. Three of the reference buildings were considered namely, Large Office Building, Medium office Building and Small Office Building, with their input in Table 6 and Table 7.

Table 6: Inputs for the three different DOE's reference building

Parameter [unit]	Large Office Building	Medium Office Building	Small Office Building
Building total Ventilated volume [m3]	178146	19741	1559
Building Height [m]	47.5	12	3.1
Wall Area (m2)			
East	2439	399.24	177.413
West	2439	399.24	177.413
South	3661	598.92	266.104
Below Grade	3563	0	0
Roof	3563	1661	598.8
ROOF 1	**U-VALUE**	**ABS. COEFF.**	**EMISSIVITY**

Table 6 (continued)			
Large Office Building	0.26	0.85	0.85
Medium Office Building	0.26	0.85	0.85
Small Office Building	0.26	0.85	0.85
OPAQUE 1 WALL EXT			
Large Office Building	2.33	0.92	0.92
Medium Office Building	1.36	0.92	0.92
Small Office Building	2.33	0.92	0.92
OPAQUE 2 WALL UG			
Large Office Building	3.26	0.92	0.92
Medium Office Building	0	0	0
Small Office Building	0	0	0

Table 7: Secondary inputs for Energy Performance

	Large		Medium		Small	
Space Name	**Office**	**Basement**	**Office**	**NA**	**Office**	**NA**
Gross Floor Area (m2)	42,757	3,563	4982	0	511	0
Occupancy (m2/person)	18.58	37.16	18.58	0	18.58	0
Metabolic rate (W/person)	120	120	120	0	120	0
Appliance (W/m2)	10.76	10.76	10.76	0	10.76	0
Lighting (W/m2)	16.15	7.53	16.9	0	19.48	0
Outdoor Air (liter/s/person)	10.00	10.00	10	0	10.00	0
DHW (liter/m2/month)	2.71	2.71	2.92	0	2.88	0

4.3 City/Climate Modeling

Table 8 to Table 12 shows the thermo-physical characteristics of the building envelope in Atlanta, Chicago, Los Angeles, Miami and Phoenix respectively.

Table 8: Atlanta Climate Data used for different building

Atlanta			
ROOF 1	**U-VALUE**	**ABS. COEFF.**	**EMISSIVITY**
Large Office Building	0.41	0.85	0.85
Medium Office Building	0.41	0.85	0.85
Small Office Building	0.41	0.85	0.85
OPAQUE 1 WALL EX			
Large Office Building	1.65	0.92	0.92
Medium Office Building	0.74	0.92	0.92
Small Office Building	1.65	0.92	0.92
OPAQUE 2 WALL UG			
Large Office Building	0.65	0.92	0.92
Medium Office Building	0	0	0
Small Office Building	0	0	0

Table 9: Chicago Climate Data used for different building

Chicago			
ROOF 1	**U-VALUE**	**ABS. COEFF.**	**EMISSIVITY**
Large Office Building	0.3	0.85	0.85
Medium Office Building	0.3	0.85	0.85
Small Office Building	0.3	0.85	0.85
OPAQUE 1 WALL EX			
Large Office Building	0.57	0.92	0.92
Medium Office Building	0.47	0.85	0.85
Small Office Building	0.57	0.92	0.92
OPAQUE 2 WALL UG			
Large Office Building	0.48	0.92	0.92
Medium Office Building	0	0	0
Small Office Building	0	0	0

Table 10: Los Angeles Climate Data Used for different building

Los Angeles			
ROOF 1	**U-VALUE**	**ABS. COEFF.**	**EMISSIVITY**
Large Office Building	0.57	0.85	0.85
Medium Office Building	0.57	0.85	0.85
Small Office Building	0.57	0.85	0.85
OPAQUE 1 WALL EX			
Large Office Building	2.38	0.92	0.92
Medium Office Building	1.25	0.92	0.92
Small Office Building	2.38	0.92	0.92
OPAQUE 2 WALL UG			
Large Office Building	3.26	0.92	0.92
Medium Office Building	0	0	0
Small Office Building	0	0	0

Table 11: Miami Climate Data used for different building

Miami			
ROOF 1	**U-VALUE**	**ABS. COEFF.**	**EMISSIVITY**
Large Office Building	0.42	0.85	0.85
Medium Office Building	0.42	0.85	0.85
Small Office Building	0.42	0.85	0.85
OPAQUE 1 WALL EX			
Large Office Building	2.38	0.92	0.92
Medium Office Building	3.13	0.92	0.92
Small Office Building	2.38	0.92	0.92
OPAQUE 2 WALL UG			
Large Office Building	3.26	0.92	0.92
Medium Office Building	0	0	0
Small Office Building	0	0	0

Table 12: Phoenix Climate Data used for different building

Phoenix			
ROOF 1	**U-VALUE**	**ABS. COEFF.**	**EMISSIVITY**
Large Office Building	0.26	0.85	0.85
Medium Office Building	0.26	0.85	0.85
Small Office Building	0.26	0.85	0.85
OPAQUE 1 WALL EX			
Large Office Building	2.33	0.92	0.92
Medium Office Building	1.36	0.92	0.92
Small Office Building	2.33	0.92	0.92
OPAQUE 2 WALL UG			
Large Office Building	3.26	0.92	0.92
Medium Office Building	0	0	0
Small Office Building	0	0	

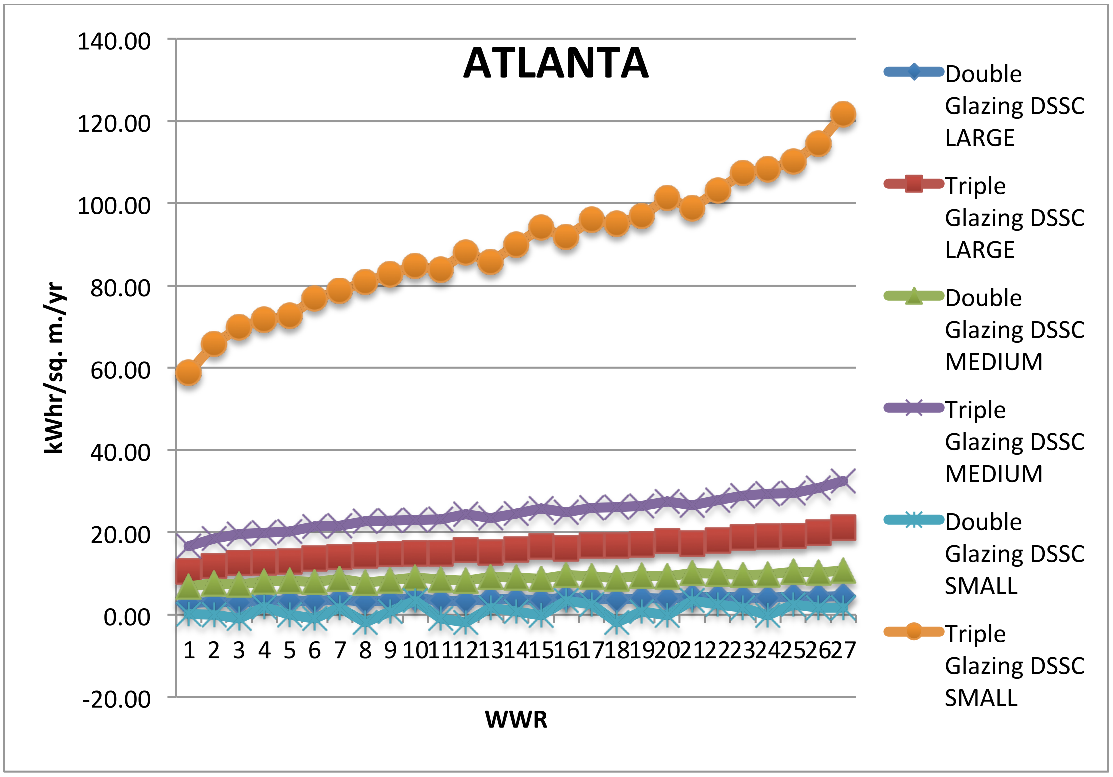
CHAPTER 5. RESULTS

Here these charts (Chart 1 to Chart 5) basically shows the results in terms of energy efficiency of the buildings. These charts shows the energy savings on per unit floor area of the building, with respect to the Business as Usual or basic model i.e., Double Glazing with inert gas window. Therefore each chart has six readings, which contains two for each of the Large, Medium and Small buildings along with both of the BIPV models. Therefore each chart shows one of the five cities considered for this study.

In terms of energy efficiency, it reflects that with increase in area allocation for the BIPV, net energy savings per unit floor area also increases. But simultaneously, it can also be observed that particularly in the Small office buildings, Triple Glazing DSSC model performs exceptionally well. So, with respect to the energy efficiency, it makes complete sense to go with the Triple Glazing model of BIPV.

5.1 Atlanta

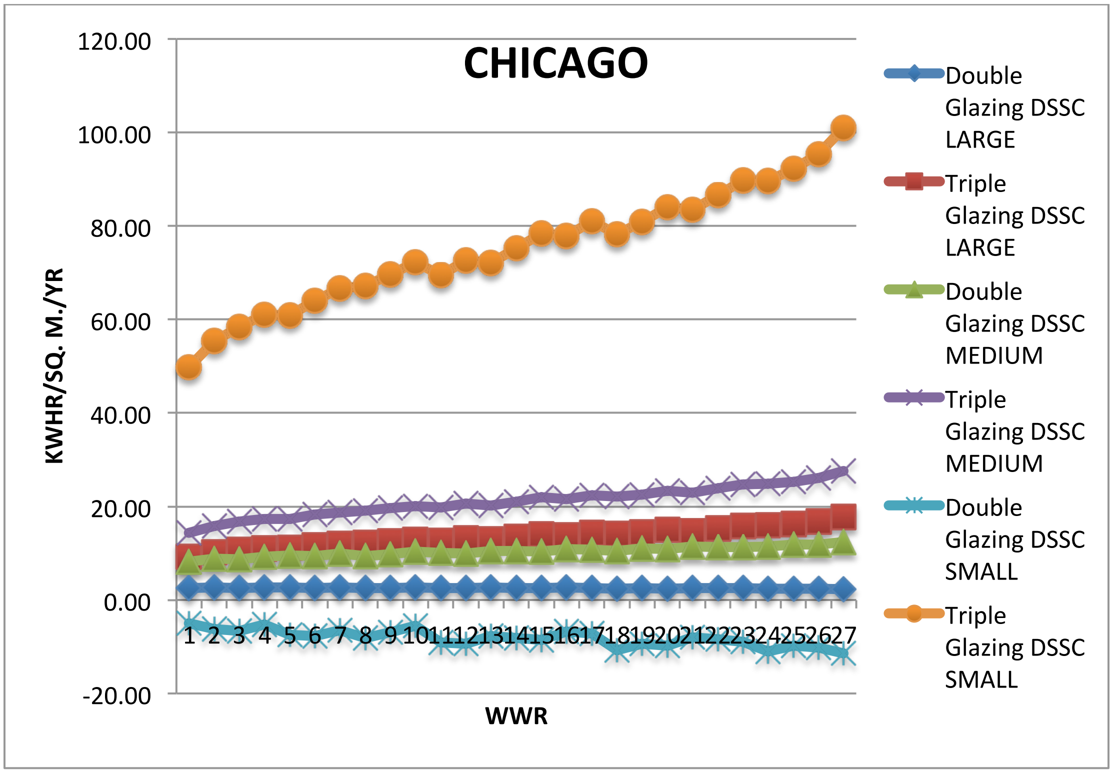
Chart 1: Delta Energy Savings per unit floor area for Atlanta



As energy savings in Double Glazing BIPV in Small office building is negative in several WWR combination, therefor it definitely do not makes sense to consider Double glazing BIPV for Small and Large office buildings in Atlanta.

5.2 Chicago

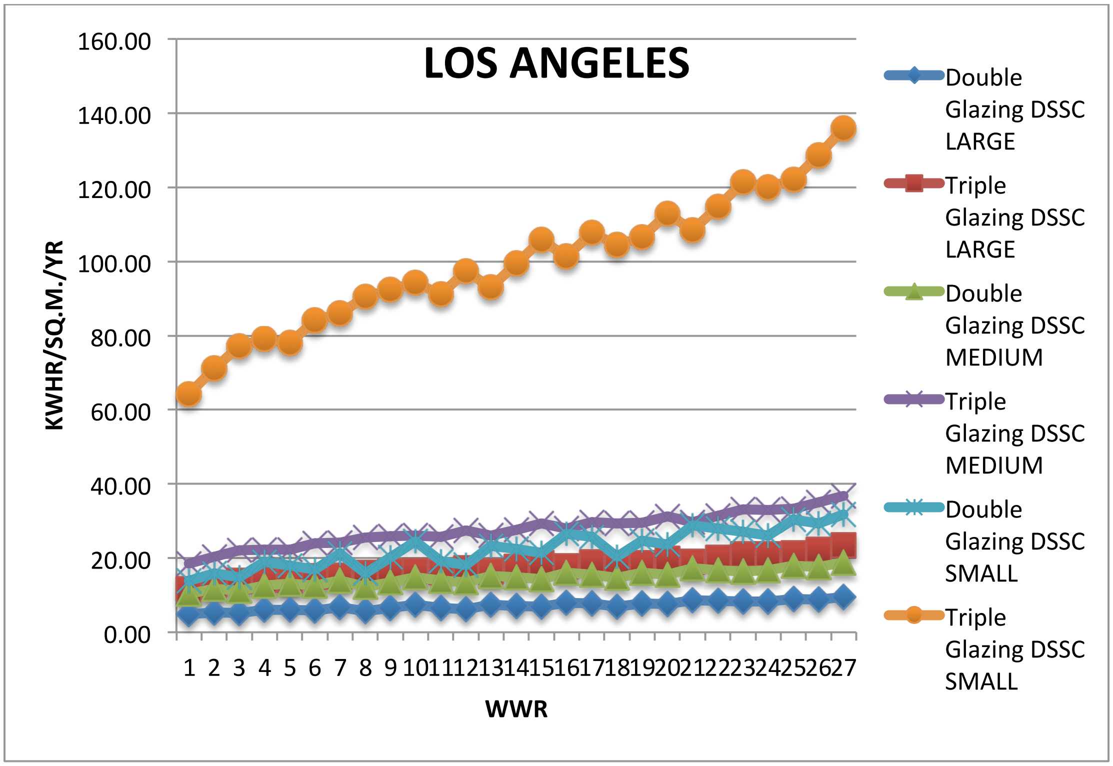
Chart 2: Delta Energy Savings per unit floor area for Chicago



As energy savings in Double Glazing BIPV in Small office building is negative in several WWR combination, therefor it definitely do not makes sense to consider Double glazing BIPV for Small and Large office buildings in Chicago.

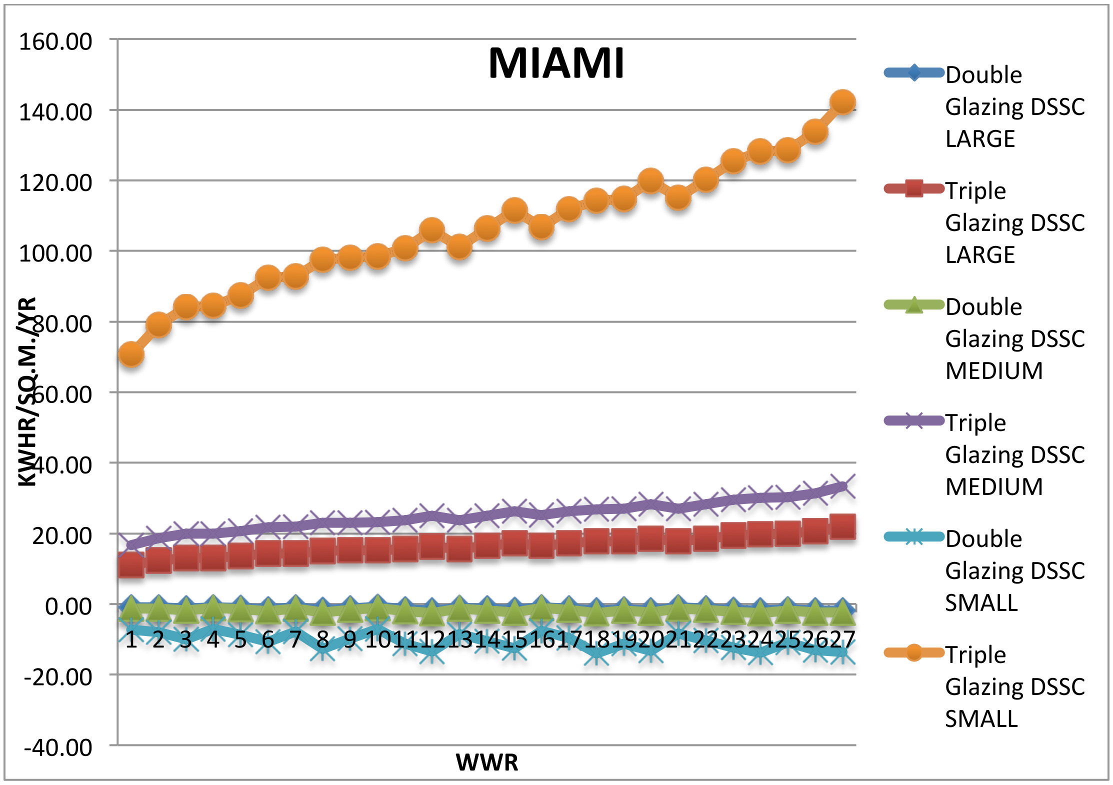
5.3 Los Angeles

Chart 3: Delta Energy Savings per unit floor area for Los Angeles



5.4 Miami

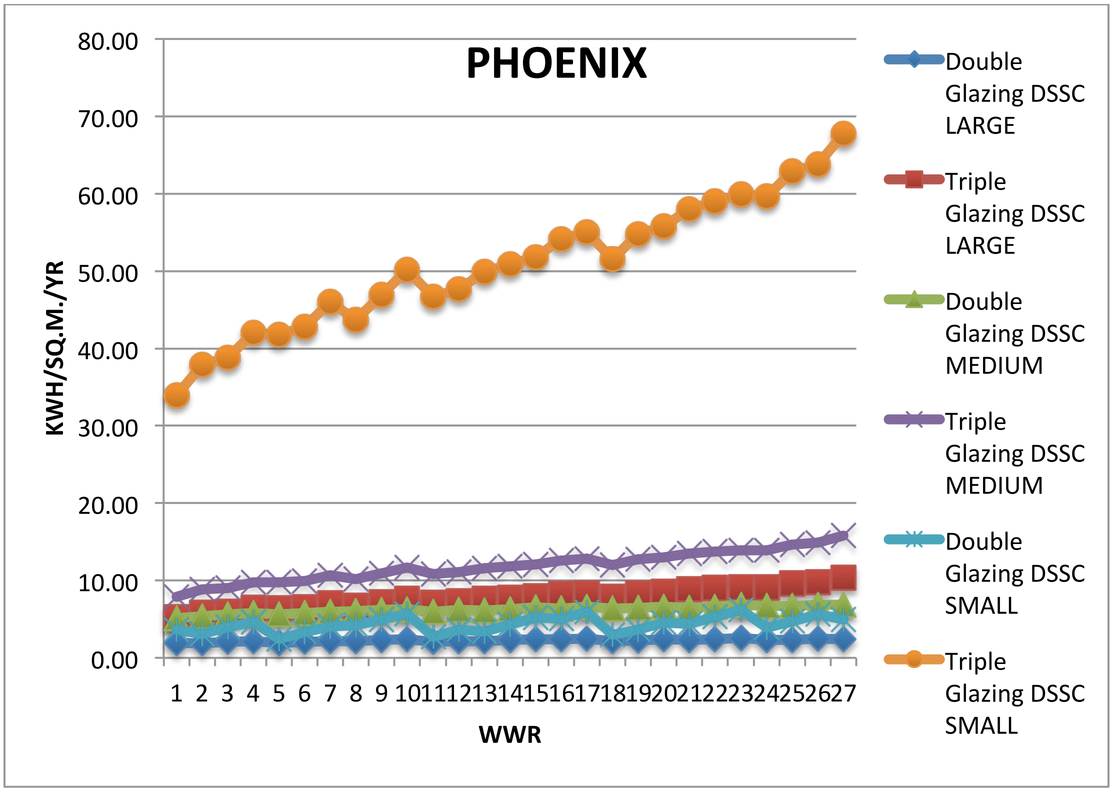
Chart 4: Delta Energy Savings per unit floor area for Miami



As energy savings in Double Glazing BIPV in Small, Medium and Large office building is negative in several WWR combination, therefor it definitely do not makes sense to consider Double glazing BIPV for Small and Large office buildings in Miami.

5.5 Phoenix

Chart 5: Delta Energy Savings per unit floor area for Phoenix



CHAPTER 6. ECONOMICS AND OPTIMIZATION

In order to understand the economics of this BIPV model, we conduct a optimization with the aim to find the best technologies that meet a given energy saving for lowest cost. The cost are the marginal cost of selected technologies over a given baseline. The benefits are dollar savings in consumed energy as well as dollar savings due to decreased demand charges. For the latter I have considered a (arbitrarily chosen) Peak Load Pricing Policy. Under this pricing mechanism, I have considered threshold energy consumption. It has been assumed that all of the loads (on monthly basis) below this threshold value are priced on a fixed rate of electricity, while the loads above this threshold value attracts a Peak Demand Charge. For this study, the factor for peak demand charge is decided by the following equation –

Equation 1: Determining Peak Factor

$$\sum_{i=1}^{12}(E_{del_i} - E_{threshold}) * Peak\ Factor = 50\% * \ Annual\ E_{Del} * Unit\ elelctricity\ cost$$

This formula is based on the logic that generally one – third of the total electricity bill is the portion covered because of the Peak Demand charges. This pricing system is used only for the load above the threshold number. Therefore, based on this equation total cost of electricity is decided by break into two parts where first part is the load under threshold value time's unit cost of electricity and second part constitutes the monthly used electricity above the threshold value times Peak Factor. This threshold value in this model is decided by considering 70% of the highest electricity-consuming month's electricity value.

There are two aspects of the Optimizations in this study, which are listed below –

6.1.1 Operational Aspects.

This aspect is mainly focused on the achievement of an ultra-energy efficiency target interpreted in terms of money. The ultra energy efficiency target is formulated in this study as the largest dollar saving for a given kWh consumption savings target. The total annual price of electricity becomes the objective function to be minimized:

Equation 2: Peak Demand Pricing

$$[(E_{Del} \ * \$/kwhr) + (E_{Del\ above\ threshold} * (Peak\ Factor)]$$

For this study the cost of for the below mentioned technologies were not considered, because the objective was to understand that what is the maximum level of efficiency that can be achieved during the operation of the building. For the purpose of this study, following technologies were considered, along with the variable option among these technologies –

1. Building Energy Management System
    a. No building automation function
    b. Adapting the operations of the building and technical systems to users need
    c. Optimizing the operation by the tuning of the different controllers, standard alarming and monitoring functions

   d. Detecting faults of building and technical systems and providing support to the diagnosis of these faults, Reporting information regarding energy consumption, indoor conditions, and possibilities for improvement

2. Building Integrated Photo Voltaics (BIPV)
   a. Business As Usual Model with regular Double pane window
   b. Triple Panel Hybrid model of BIPV with Inter Gas and DSSC.
3. Heat Recovery Types
   a. No heat recovery
   b. Heat exchange plates or pipes
   c. Two-element-systems
   d. Loading cold with air-conditioning
   e. Heat pipes
   f. Slowly rotating or intermittent heat exchangers.

As mentioned above that objective function for this optimization was the annual utility bill. Also for easy understanding only three cases out of 27 window with lowest, highest and mean option in terms of area allocation for BIPVs i.e., 40%, 60% and 80% on each of East, West and South facade. Here Table 13 to Table 18 shows the minimum possible money to be spent under the following combinations, for per unit of gross floor area on the annual basis. In each of these tables shaded cell shows the most efficient case.

Table 13: Operational Electricity Bill Optimization for Atlanta

Atlanta	WWR Combination	Large Office	Medium Office	Small Office
Optimized Electric Bill ($/sq.m./yr)	1	21.61	22.43	23.67
Optimized Combination	1	1(d), 2(b), 3(f)	1(d), 2(b), 3(f)	1(d), 2(b), 3(f)
Optimized Electric Bill ($/sq.m./yr)	14	21.29	21.79	22.01
Optimized Combination	14	1(d), 2(b), 3(f)	1(d), 2(b), 3(f)	1(d), 2(b), 3(f)
Optimized Electric Bill ($/sq.m./yr)	27	21.40	22.01	22.43
Optimized Combination	27	1(d), 2(b), 3(f)	1(d), 2(b), 3(f)	1(d), 2(b), 3(f)

Table 14: Operational Electricity Bill Optimization for Chicago

Chicago	WWR Combination	Large Office	Medium Office	Small Office
Optimized Electric Bill ($/sq.m./yr)	1	20.44	20.83	21.57
Optimized Combination	1	1(d), 2(b), 3(f)	1(d), 2(b), 3(f)	1(d), 2(b), 3(f)
Optimized Electric Bill ($/sq.m./yr)	14	20.13	20.10	21.40
Optimized Combination	14	1(d), 2(b), 3(f)	1(d), 2(b), 3(f)	1(d), 2(b), 3(f)
Optimized Electric Bill ($/sq.m./yr)	27	20.22	20.35	21.31
Optimized Combination	27	1(d), 2(b), 3(f)	1(d), 2(b), 3(f)	1(d), 2(b), 3(f)

Table 15: Operational Electricity Bill Optimization for Los Angeles

Los Angeles	WWR Combination	Large Office	Medium Office	Small Office
Optimized Electric Bill ($/sq.m./yr)	1	20.93	22.29	20.44
Optimized Combination	1	1(d), 2(b), 3(f)	1(d), 2(b), 3(f)	1(d), 2(b), 3(f)
Optimized Electric Bill ($/sq.m./yr)	14	20.64	21.61	18.17
Optimized Combination	14	1(d), 2(b), 3(f)	1(d), 2(b), 3(f)	1(d), 2(b), 3(f)
Optimized Electric Bill ($/sq.m./yr)	27	20.72	21.85	18.72
Optimized Combination	27	1(d), 2(b), 3(f)	1(d), 2(b), 3(f)	1(d), 2(b), 3(f)

Table 16: Operational Electricity Bill Optimization for Miami

Miami	WWR Combination	Large Office	Medium Office	Small Office
Optimized Electric Bill ($/sq.m./yr)	1	24.37	26.23	29.71
Optimized Combination	1	1(d), 2(b), 3(f)	1(d), 2(b), 3(f)	1(d), 2(b), 3(f)
Optimized Electric Bill ($/sq.m./yr)	14	24.09	25.64	27.80
Optimized Combination	14	1(d), 2(b), 3(f)	1(d), 2(b), 3(f)	1(d), 2(b), 3(f)
Optimized Electric Bill ($/sq.m./yr)	27	24.18	25.82	28.39
Optimized Combination	27	1(d), 2(b), 3(f)	1(d), 2(b), 3(f)	1(d), 2(b), 3(f)

Table 17: Operational Electricity Bill for Phoenix

Phoenix	WWR Combination	Large Office	Medium Office	Small Office
Optimized Electric Bill ($/sq.m./yr)	1	23.41	23.98	27.15
Optimized Combination	1	1(d), 2(b), 3(f)	1(d), 2(b), 3(f)	1(d), 2(b), 3(f)
Optimized Electric Bill ($/sq.m./yr)	14	22.45	22.69	21.76
Optimized Combination	14	1(d), 2(b), 3(f)	1(d), 2(b), 3(f)	1(d), 2(b), 3(f)
Optimized Electric Bill ($/sq.m./yr)	27	22.71	23.04	23.15
Optimized Combination	27	1(d), 2(b), 3(f)	1(d), 2(b), 3(f)	1(d), 2(b), 3(f)

6.1.2 Overall Cost-Benefit Analysis

This study is focused on the economics based decision making for considering the competitiveness of this BIPV technology, which in this we interpret as a technology that is among the mix of the optimal selection for a given savings target. In order to quantify the ranking of this technology, annual saving in Delivered Energy has been considered and the cost associated with it has been considered for Net Present value (NPV). Life cycle for the competitive technologies has been considered as 20 years. So the objective function for this optimization is basically the Maximum of Net Savings, which can also be expressed as –

Equation 3: Feasibility equation

$$Max.[NPV\ of\ Savings - Investment]$$

Where Net Savings is defined as reduction in Annual Delivered Energy cost from the Business as usual case. Here Table 18 to Table 22 shows the yearly money savings in terms of per unit floor area of the building. For this study, it was decided to consider two of the extreme cases and 1 mean case of Window to Wall Ratio i.e., 1, 14, 27.

Table 18: Annual Savings through BIPV Atlanta

Annual money savings with BIPV per unit floor area: Atlanta			
WWR	Large Building	Medium Building	Small Building
1	$1.23	$1.92	$6.88
14	$2.03	$3.11	$11.64
27	$1.92	$2.96	$10.89

Table 19: Annual Savings through BIPV Chicago

Annual money savings with BIPV per unit floor area: Chicago			
WWR	Large Building	Medium Building	Small Building
1	$1.1	$1.68	$5.9
14	$1.75	$2.72	$9.95
27	$1.66	$2.55	$9.19

Table 20: Annual Savings through BIPV Los Angeles

Annual money savings with BIPV per unit floor area: Los Angeles			
WWR	Large Building	Medium Building	Small Building
1	$1.33	$2.08	$7.48
14	$2.18	$3.37	$12.66
27	$2.1	$3.27	$12.13

Table 21: Annual Savings through BIPV Miami

Annual money savings with BIPV per unit floor area: Miami			
WWR	Large Building	Medium Building	Small Building
1	$1.23	$1.86	$7.96
14	$2.01	$3.07	$13.09
27	$1.91	$2.92	$12.45

Table 22: Annual Savings through BIPV Phoenix

Annual money savings with BIPV per unit floor area: Phoenix			
WWR	Large Building	Medium Building	Small Building
1	$0.78	$1.18	$5.08
14	$1.32	$2.02	$8.69
27	$1.18	$1.8	$7.76

CHAPTER 7. CONCLUSION

As discussed in the previous chapters, this Building Integrated Photo Voltaic (BIPV) technology has the potential to generate the on-site electricity. Therefore, this technology seems to be a competitive technology if the objective is to achieve the ultra energy efficient buildings. But when we consider the cost-benefit analysis for this technology, it seems that it’s not a very economic technology in the current point of time, under most of the cases.

Considering these aspects it can be considered that if the scale of use for this technology will be increased then it will bring down to cost of this technology as well. Therefore, it seems that at this point of time this technology can only be competitive enough for ultra energy efficient buildings, but at same point of time its tough for BIPV to compete with other existing energy efficient technologies for higher efficiency.

APPENDIX A. REFERENCE BUILDINGS

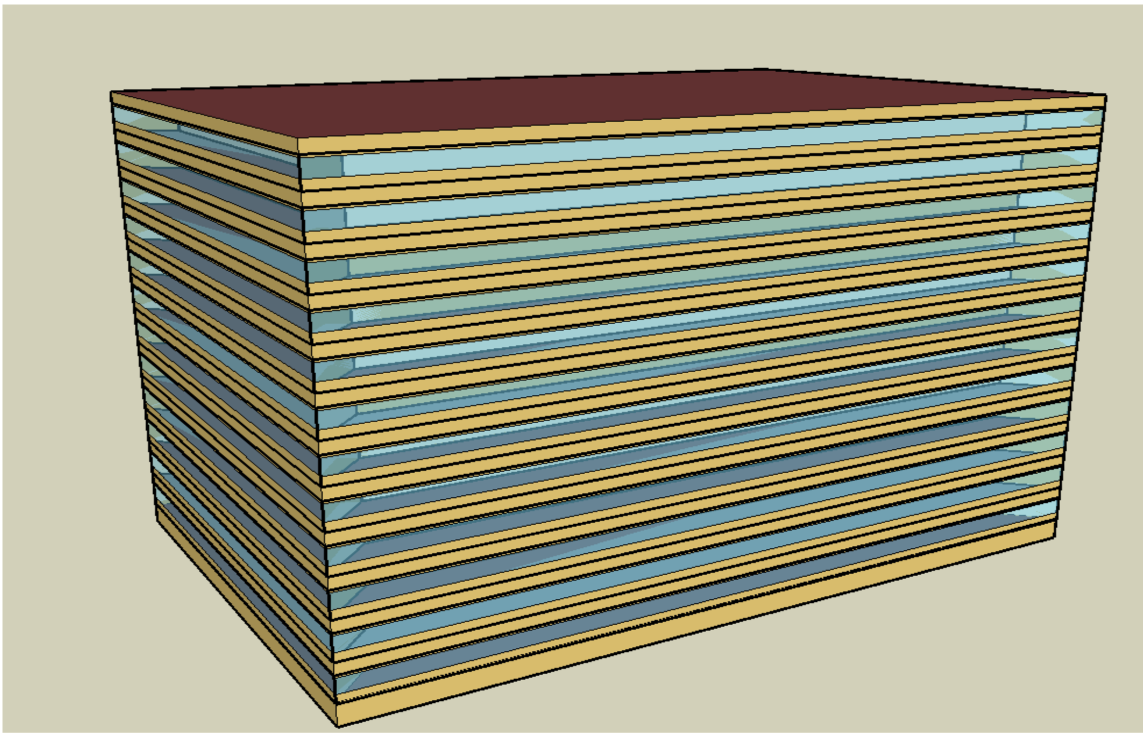


Figure 4: Large Reference Building View

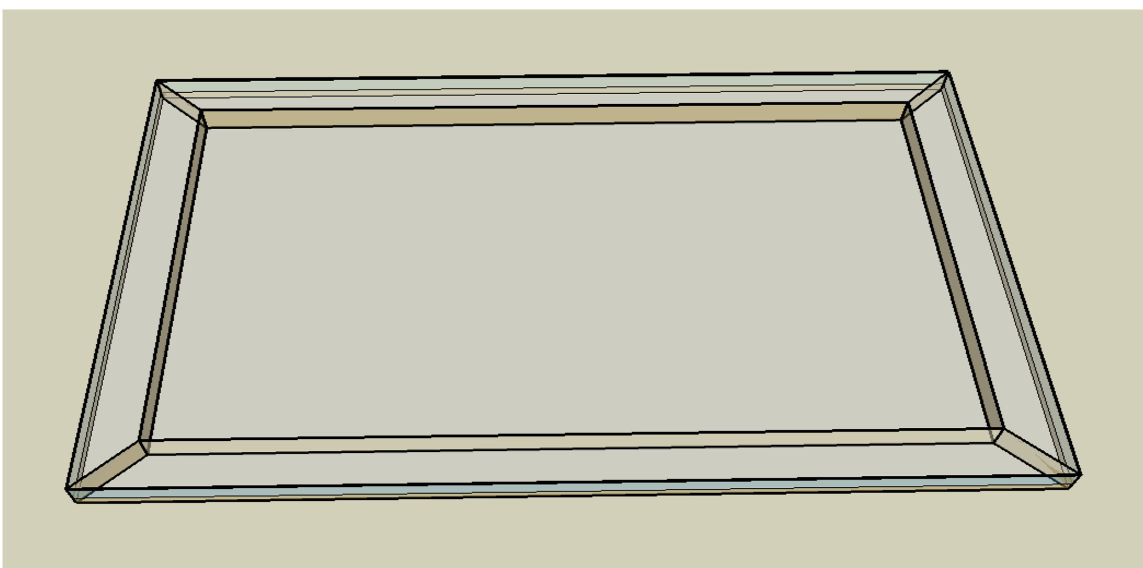


Figure 5: Large Reference Building Typical Floor Plan

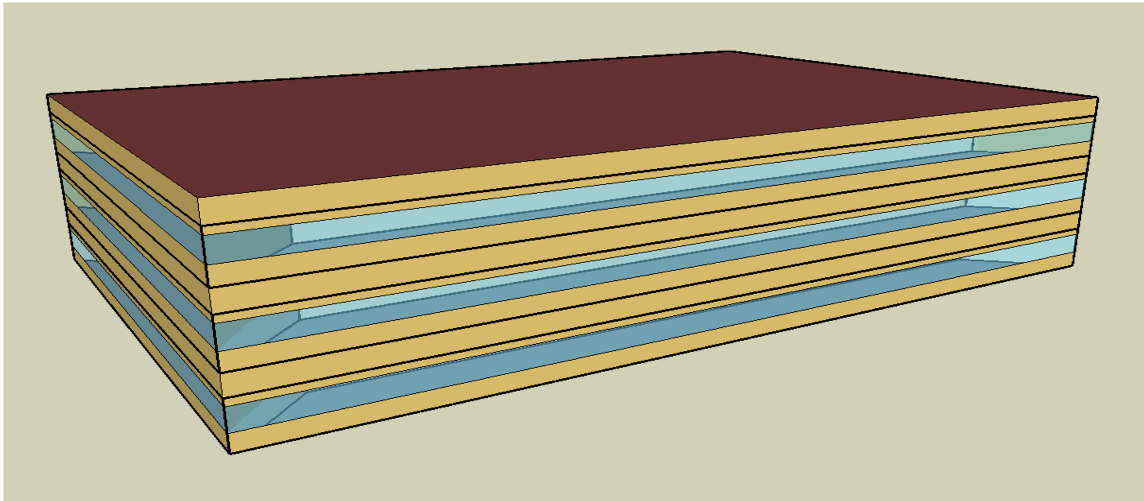


Figure 6: Medium Reference Building View

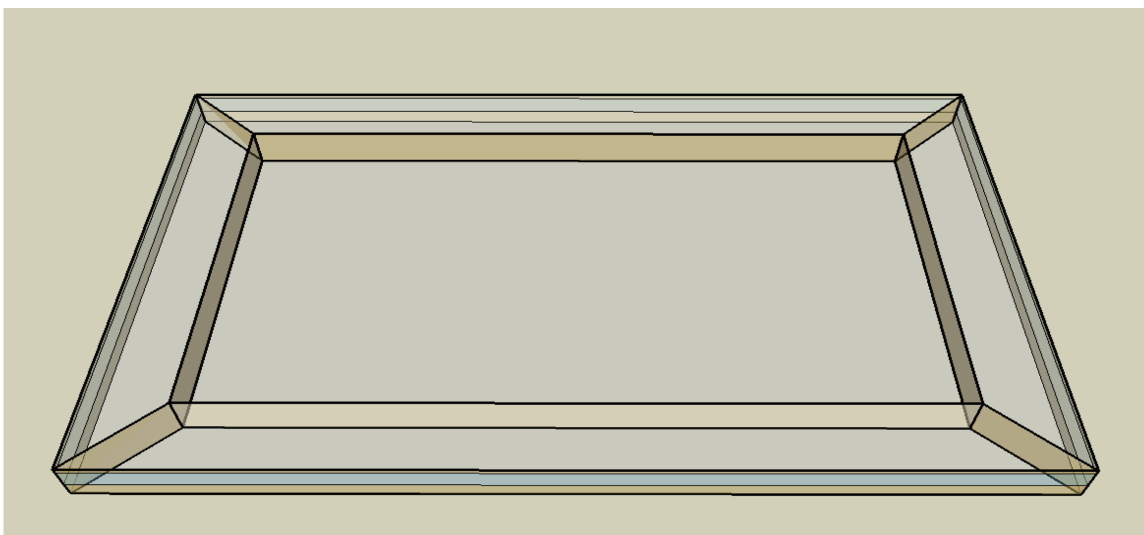


Figure 7: Medium Reference Building Typical Floor Plan

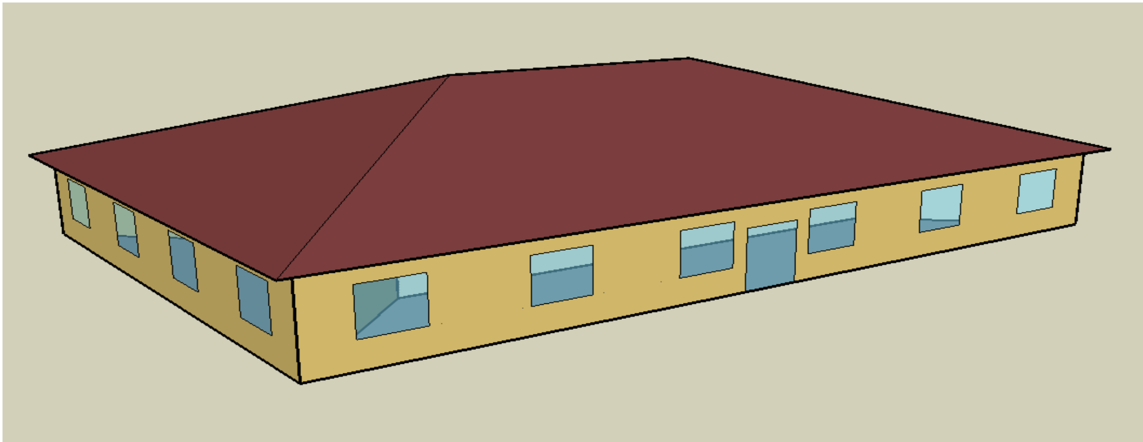


Figure 8: Small Reference Building View

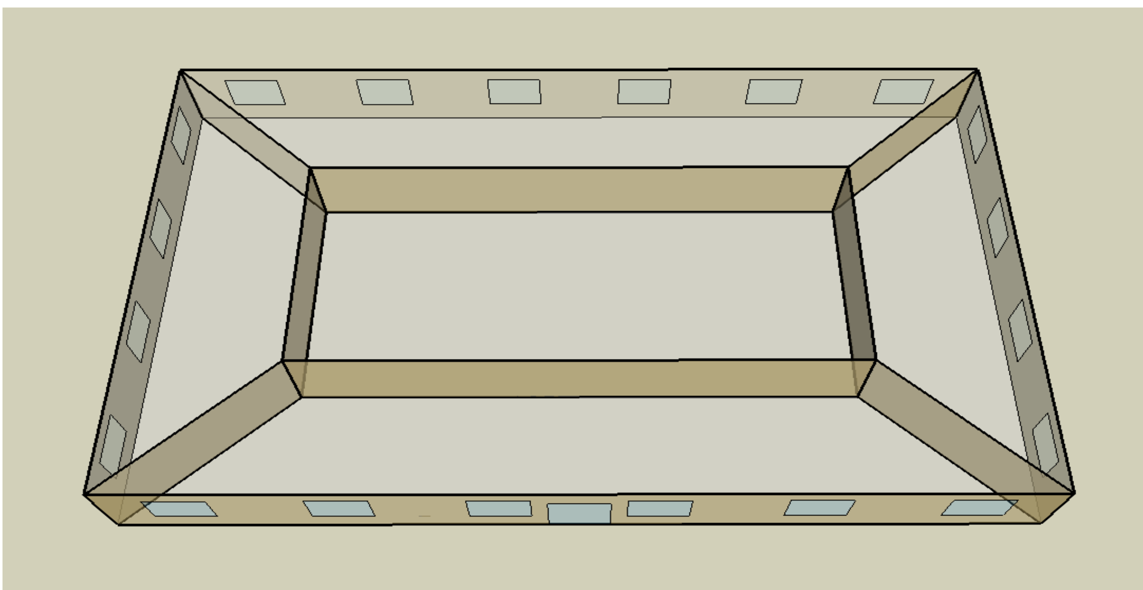


Figure 9: Small Reference Building Typical Floor Plan

REFERENCES

[1] Ragoussi, M.-E et al. Rev. Virtual Quim. (2015)

[2] Basic Research Needs for Solar Energy Utilization, U.S. Department of Energy Office of Basic Energy Sciences (2005).

[3] Mathew, S. et al, Nature Chemistry. (2014)

[4] Burschka, Julian, et al. Nature 499.7458 (2013)

[5] Giribabu, Lingamallu, Ravi Kumar Kanaparthi, and Veerapandian Velkannan. "Molecular engineering of sensitizers for dye-sensitized solar cell applications." The Chemical Record 12.3 (2012)

[6] B. O'Regan, M. Gratzel, Nature 353, 737 (1991)

[7] Valente, Júlia Maria Antunes. "Compostos pirrólicos para células foto-voltaicas." (2010)

[8] M. K. Nazeeruddin, A. Kay, R. Humpbry-Baker, E. Miiller, P.Liska, N. Vlachopoulos, M. Gratzel, J. Am. Chem. Soc. 115,6382 (1993)

[9] G. Benkö, J. Kallioinen, J. E. I. Korppi-Tommola, A. P.Yartsev, V. Sundström, J. Am. Chem. Soc. 124, 489 (2002)

[10] J. B. Asbury, R. J. Ellingson, H. N. Ghosh, S. Ferrere, A.J. Nozik, T. Lian, J. Phys. Chem. B 103, 3110 (1999)

[11] Y. Tachibana, J. E. Moser, M. Grätzel, D. R. Klug, J. R.Durrant, J. Phys. Chem. 100, 20056 (1996)

[12] A. Hinsch, J. M. Kroon, R. Kern, I. Uhlendorf, J. Holzbock, A. Meyer, J. Ferber, Prog. Photovolt.: Res. Appl. 9, 425 (2001)

[13] N.-G. Park, J. van de Lagemaat, A. J. Frank, J. Phys.Chem. B 104, 8989 (2000)

[14] K. D. Benkstein, N. Kopidakis, J. van de Lagemaat, A. J.Frank, J. Phys. Chem. B. 107, 7759 (2003)

[15] Grätzel, Michael. "Solar energy conversion by dye-sensitized photovoltaic cells." *Inorganic chemistry* 44.20 (2005): 6841-6851.

[16] N.-G. Park, C. Kim et al., Chem. Commun., 4887 (2007)

[17] Pagliaro, M. et al, Nanochemistry aspects of titania in dye-sensitized solar cells., Energy and Environmental Science (2009)

[18] Docampo, P. et al, Lessons Learned: From Dye-Sensitized Solar Cells to All-Solid-State Hybrid Devices., Advanced Materials (2014)

[19] Hagfeldt, A.; Grätzel, M. Light-Induced Redox Reactions in Nanocrystalline Systems., Chemical Reviews (1995)

[20] https://windows.lbl.gov/software/window/window.html

[21] ASHRAE Fundamentals (SI) 2009 F15 Table 4: U-Factor and Table 10: Solar Energy Transmittance

[22] Oviri O.K. et al. (2013)

[23] Max Halabi, California state science fair (2013)

[24] Excel spreadsheet. Pranav.

[25] Solar Direct, “Solar Electric System Sizing,” Accessed 07 Dec 2016, http://www.solardirect.com/pv/systems/gts/gts-sizing-sun-hours.html.

[26] “Commercial and Residential Hourly Load Data,” *OpenEi*, Accessed 07 Dec 2016, https://en.openei.org/community/blog/commercial-and-residential-hourly-load-data-now-available-openei.

[27] “Solar Purchase Tariff,” *Georgia Power*, Accessed 07 Dec 2016, http://www.georgiapower.com/docs/rates-schedules/renewable-nonrenewable/11.20_SP.pdf.

[28] Deliso, R., “Understanding Peak Demand Charges,” *EnergySmart*, Accessed 07 Dec 2016, http://www.georgiapower.com/docs/rates-schedules/renewable-nonrenewable/11.10_RNR.pdf.

[29] http://www.energysmart.enernoc.com/understanding-peak-demand-charges/.

[30] LiFePO4 specifications, *AA Portable Power Corps*, Accessed 07 Dec 2016, http://www.batteryspace.com/custom-polymer-lifepo4-battery-pack-28-8v-20ah-576wh-20a-rate-with-customer-provide-pcb-54-0.aspx.

[31] “LiFePO4 Battery,” *ClevaPower*, Accessed 07 Dec 2016, http://clevapower.en.made-in-china.com/product/rSkJgByPLbVZ/China-24V-100ah-Lithium-Iron-Phosphate-Battery-for-Solar-System.html.

[32] “What is Demand-Side Management?” *EnerNoc*, Accessed 07 Dec 2016. http://www.enernoc.com/our-resources/term-pages/what-is-demand-side-management.

[33] “Demand Side Management,” PacifiCorp, Accessed 07 Dec 2016, http://www.pacificorp.com/es/dsm.html.

[34] “Demand Response,” *Energy.Gov*, Accessed 07 Dec 2016, http://energy.gov/oe/technology-development/smart-grid/demand-response.

[35] Corson, R., Regan, R., Carlson, S., “Implementing energy storage for peak-load shifting,” *Consulting – Specifying Engineer*, Accessed 07 Dec 2016, http://www.csemag.com/single-article/implementing-energy-storage-for-peak-load-shifting/95b3d2a5db6725428142c5a605ac6d89.html.

[36] “What is energy efficiency?” *Lawrence Berkeley National Laboratory*, Accessed 07 Dec 2016, http://eetd.lbl.gov/ee/ee-1.html.